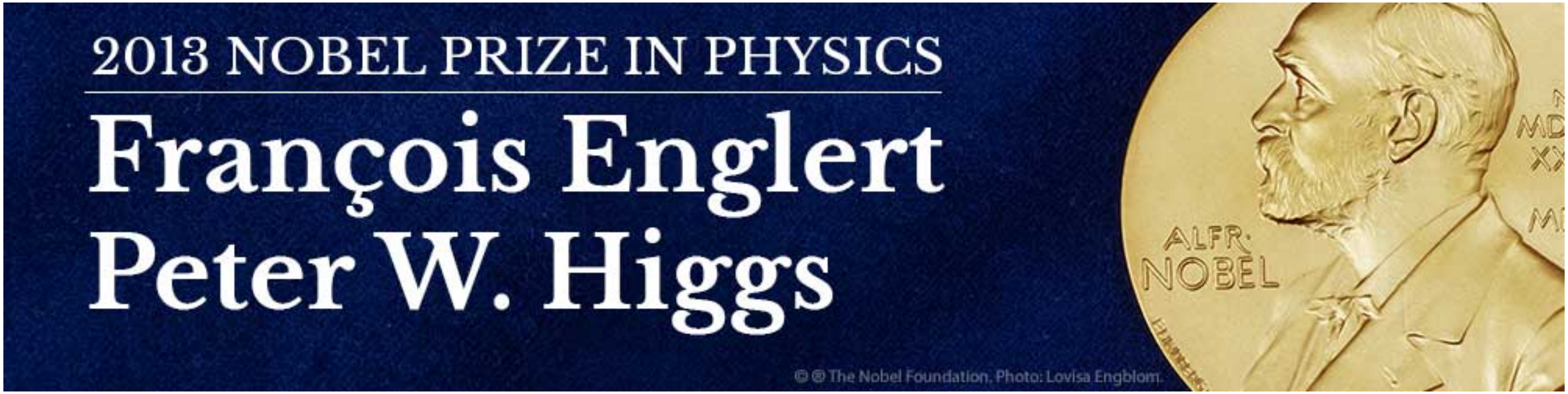
9 Oct 2013 @IPMU

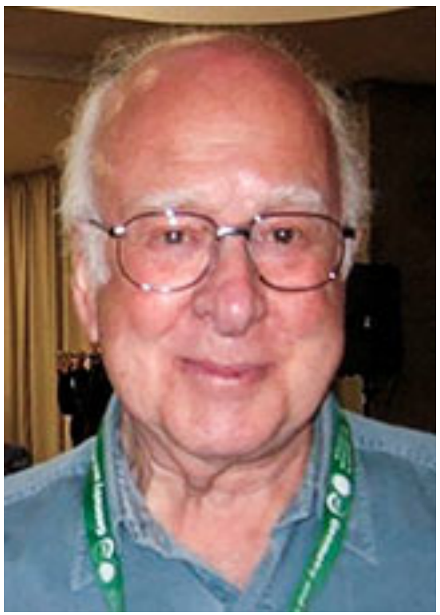
An implication of 126 GeV Higgs boson for Planck scale physics

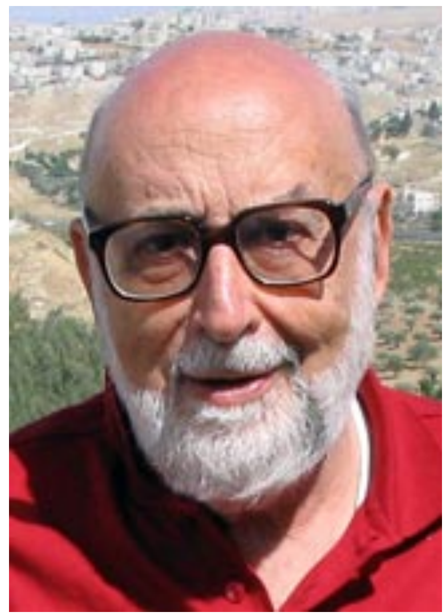
- Flatland from Naturalness and Stability -

Satoshi Iso

KEK
&
Sokendai

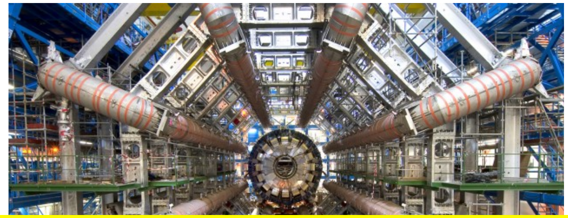




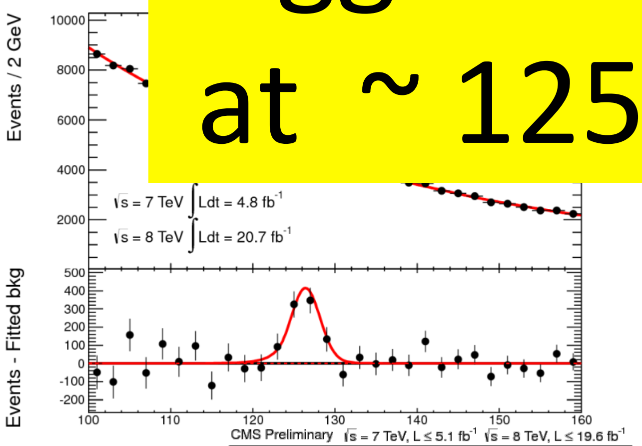


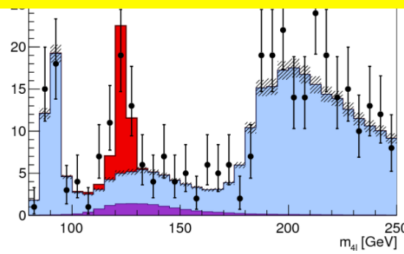
R. Brout (1928 -May 2011)

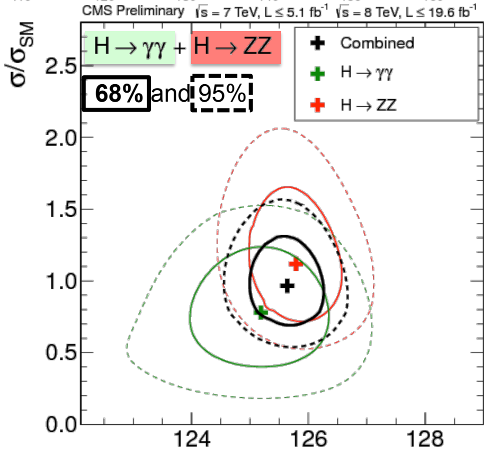
Congratulations !!

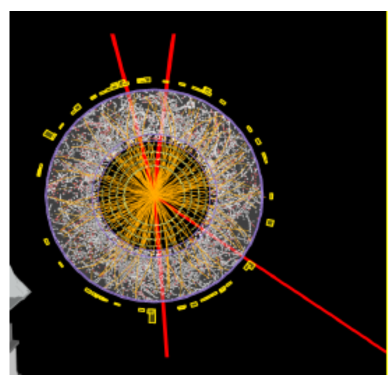


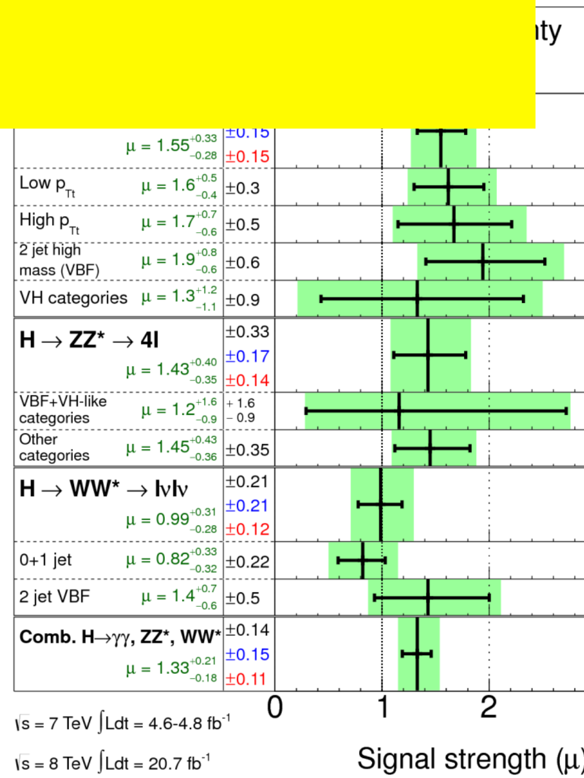
Higgs boson was discovered at ~ 125.5 GeV







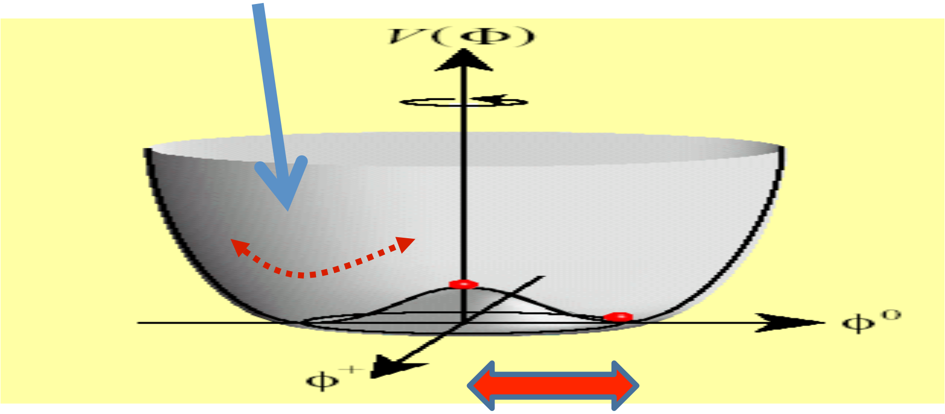




An (elementary) scalar exists !

And it has a rather
shallow potential

$m_H = 126\ \mathrm{GeV}$



$v = 246\mathrm{GeV}$

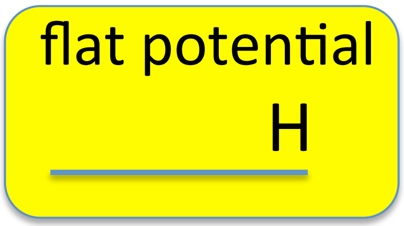
What is the origin of the Higgs potential ?
Why and how does the EWSB occur ?

In this talk I will show that

Higgs potential at IR can be radiatively generated from a completely flat potetial at UV.

UV

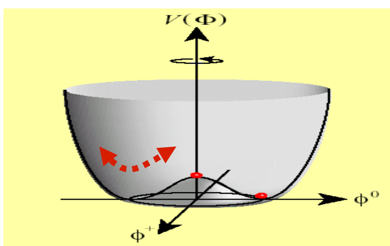
M_{PL}



$$V(H) = 0 \quad @M_{PL}$$

IR

M_{EW}



$$V = -\mu^2|H|^2 + \lambda(|H|^2)^2$$

An implication of 126 GeV Higgs boson for Planck scale physics

- Flatland from Naturalness and Stability -

based on collaborations

N.Okada (Alabama), Y.Orikasa (Osaka), SI

Phy.Lett.B276(2009) 81 & Phys.Rev. D80 (2009) 115007

"Classically conformal B-L extension of the SM"

H.Aoki (Saga), SI Phys.Rev.D86(2012)013001

"Revisiting the Naturalness problem"

Y.Orikasa (Osaka), SI

PTEP 2013,023B08 & arXiv:1304.0293

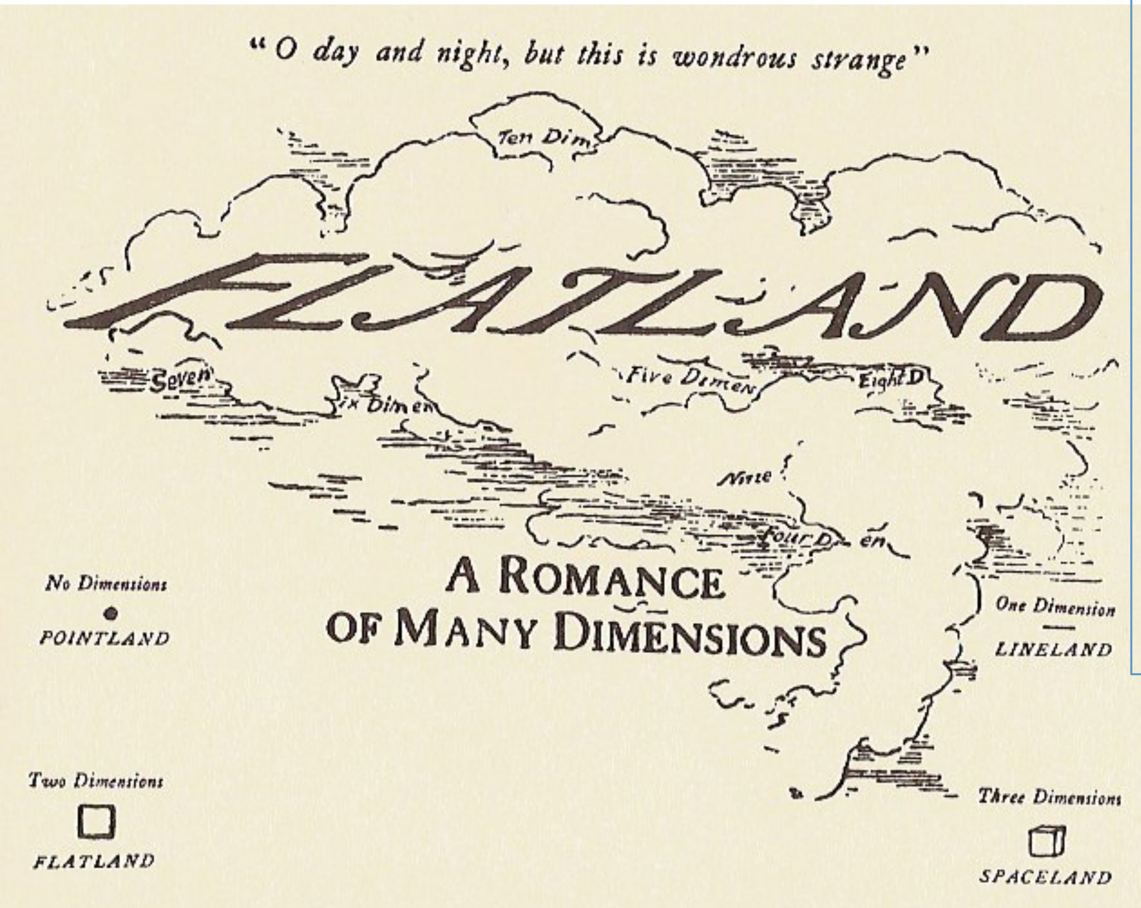
"TeV scale B-L model with a Flat Higgs potential at the Planck scale"

- in view of the Hierarchy problem –

M.Hashimoto (Chubu), Y.Orikasa(Osaka), SI

"Electroweak symmetry breaking in Flatland" *to appear soon*

Flatland - A romance of many dimensions -



A satirical (風刺) novel written by Edwin A. Abbott in 1884 (English schoolmaster)

Abbott used a fictional two-dim world of Flatland to offer pointed observations on the social hierarchy of Victorian culture.

from Wikipedia

A story on a flat two-dimensional space =Flatland
A three dimensional space with height is called Spaceland

Outline

Motivation for $V(H)=0$ @ M_{PL}

[1] Revisiting the Naturalness Problem

[2] Stability of SM vacuum = 126 GeV M_H

Radiative generation of $V(H)$ @M_{EW}

[3] "classically conformal B-L extension of SM"

Scalar potential is partially generated.

[4] "Flatland model" -- a variant of B-L model

Complete generation of the scalar potential

Today I do not talk about the Phenomenology of the model

[5] Neutrino oscillation, Leptogenesis, etc.

H Aoki, SI : 1201.0857
Y Orikasa, SI : 1210.2848
SI : 1304.0293

[1] Naturalness problem

Bardeen (1995 @ Ontake summer school)

Standard model is classically scale invariant if Higgs mass term is absent.

$$T^{\mu}_{\mu} = 0$$

Quantum anomaly breaks the invariance (if not conformal)

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i$$

The common wisdom is that the breaking is not soft and we have

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i + const.\ \Lambda^2\bar{h}h$$

Bardeen argued that it should be

$$T^{\mu}_{\mu} = \beta(\lambda_i)O_i + \delta m^2\bar{h}h$$

$$\delta m^2 = const. \times m^2 \neq const. \times \Lambda^2$$

It is commonly stated that naturalness problem is caused by quadratic divergence of a scalar mass.

Is quadratic divergence physically relevant?

Bardeen (1995)

H Aoki, SI (2012)

3 reasons why I think power divergences are physically irrelevant in the IR effective theory:

(1) they can be always subtracted
unlike multiplicatively renomalized logarithmic divergences

(2) In the Wilsonian RG, power divergences determine the position of the critical surfaces, and have nothing to do with the RG flow.

(3) power divergences are not generally covariant.

ex.) EMT of a massive field on a curved space-time

Energy=$\int dk\, \omega\, k^2$, pressure=$\int dk\, k^4/3\omega$, $\omega^2=(k^2+m^2)$

So Λ^4 term has w=1/3 (so it is not proportional to $g^{\mu\nu}$)

$m^4 \log \Lambda$ term gives the covariant EMT with w=-1 (DE).

Classification of divergences

1. Power divergences Λ^2
   It can be simply subtracted at UV scale, and gives a boundary condition at UV. Once subtracted, no longer appears.

---

2. Logarithmic divergences $m^2 \log(\Lambda/m)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right)$$

3. Large Logarithmic divergences: $M^2 \log(\Lambda/M)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right) + \boxed{\frac{M^2}{8\pi^2}\lambda_{mix}}$$

$$\delta m^2 = \frac{\lambda_{mix} M^2}{16\pi^2}\log(M^2/m^2)$$

m	<<	M
Low energy physics		High energy physics

It is important to distinguish 1 and 3.

In order to solve the "naturalness problem",
of IR theory embedded in UV completion theory, we need to control

(a) " M_{PL}^2 term" → correct boundary condition at Planck

The most natural b.c. is NO MASS TERMS at Planck

(= classical conformal)

$$V = -\cancel{\mu^2|H|^2} + \lambda(|H|^2)^2$$

(b) "large logarithmic divergence" by mixing with a large mass M

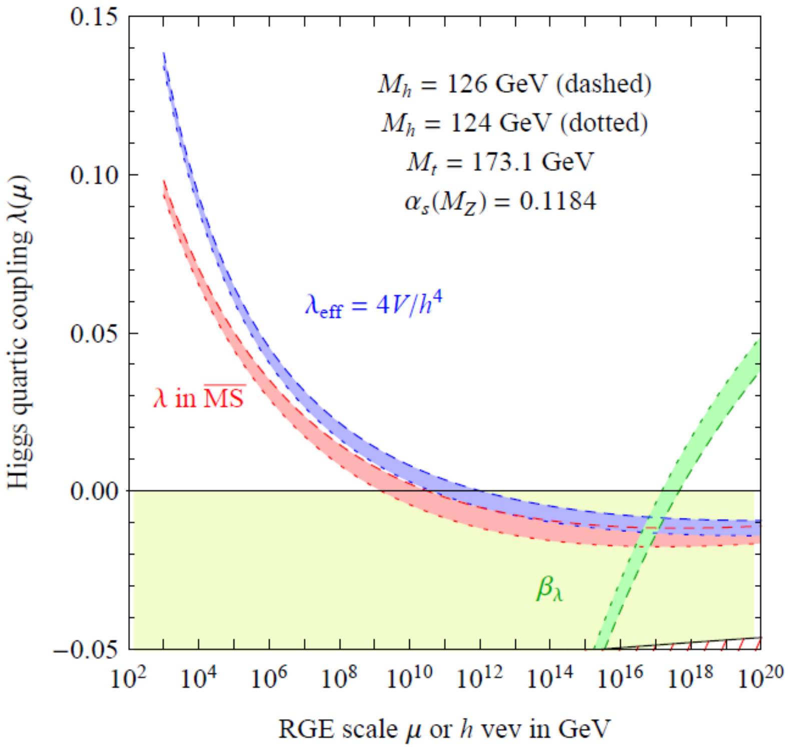
No large intermediate scales beyond EW up to Planck

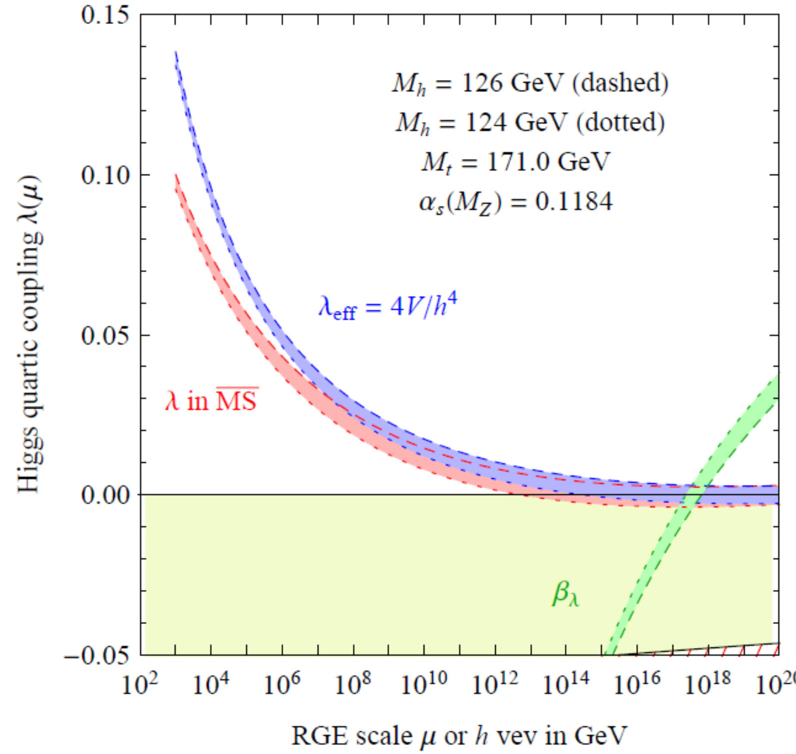
"Classical conformal theory with no intermediate scale"
can be an alternative solution to the naturalness problem.

Foot Kobakhidze Macdonald Volkas (07), Shaposhnikov (07), Meissner Nicolai (07),
SI, Okada,Orikasa (09), Holthausen Lindner Schmidt (09), Nunneley Pilaftsis (10), Iwashita(11),
Lee Pilaftsis(12), Englert Jaekel Khoze Spannovski (13), Chun Jun Lee (13), Carone Ramos(13), , , ,

It is recently called "physical naturalness".

[2] Stability of Vacuum





New physics at 10^{12} GeV
is necessary to stabilize the vacuum

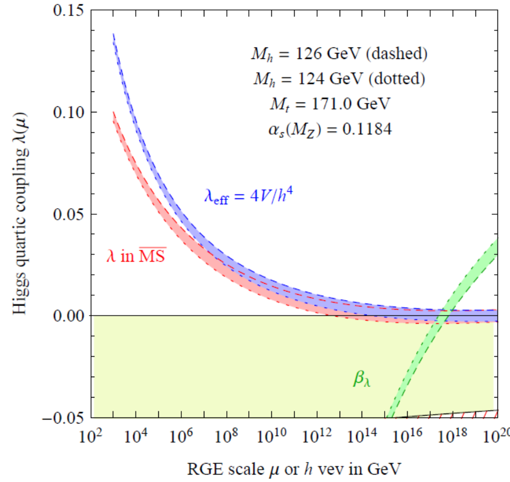
Flat Higgs potential
at Planck scale

$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2\ {\rm GeV}}{0.9\ {\rm GeV}} \right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0\ {\rm GeV}.$$

Elias-Miro et.al.(12)
Alkhin, Djouadi, Moch (12)

very sensitive to top quark mass

(Also sensitive to higher dim op. and nonperturbative behavior of RG)

If this 

is the case ?

$$\lambda(\Lambda_0) = \beta_\lambda(\Lambda_0) = 0$$

$$V = -\mu^2|H|^2 + \cancel{\lambda(|H|^2)^2}$$

Direct window to Planck scale

Frogatt Nielsen (96)
M.Shaposhnikov (07)

[3] “classically conformal B-L model”

N Okada, Y Orikasa, SI
0902.4050 (PLB)
0909.0128 (PRD)
Y Orikasa, SI
1210.2848 (PTEP)

Indication on the Higgs potential

$$V = -\cancel{\mu^2|H|^2} + \cancel{\lambda(|H|^2)^2}$$

flat potential

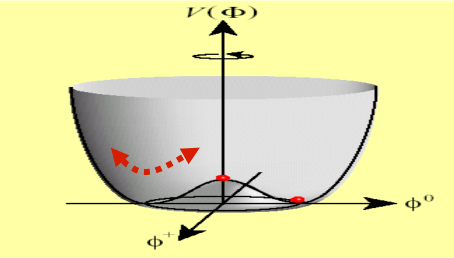
ϕ

flat potential V(H)=0 at Planck.

M_{PL}

Radiatively generate

Coleman-Weinberg mechanism



EWSB @ M_{EW}

Review of symmetry breakings: negative mass or radiative breaking

（1）SSB by negative mass term

$$V = \frac{\lambda}{4}h^4 + \frac{\mu^2}{2}h^2 \quad (\mu^2 < 0) \longrightarrow \quad m_h^2 = 2|\mu^2| = \boxed{2\lambda\langle h\rangle^2}$$

（2）Coleman-Weinberg mechanism (radiative breaking)

$$V_{eff} = \underbrace{\frac{\lambda h^4}{4}}_{\text{tree}} + \underbrace{Bh^4\left(\ln\left(\frac{h^2}{\langle h\rangle^2}\right) - \frac{25}{6}\right)}_{\text{1-loop}} \qquad B = \frac{3}{64\pi^2}\left(3\lambda^2 + \frac{3g^4 + 2g^2g'^2 + g'^4}{16} - Y_t^4\right)$$

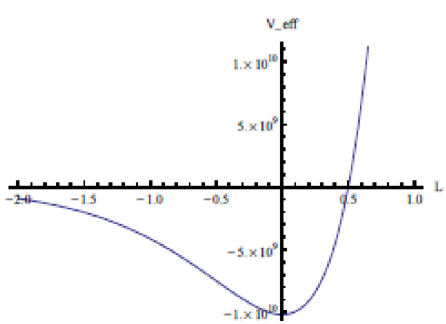


図 2.1 improve されていない有効ポテンシャル

Higgs mass is given by

$$V''|_{\langle h\rangle} = m_h^2 = 8\underline{B}\langle h\rangle^2 = \boxed{\frac{6}{11}\lambda\langle h\rangle^2}$$

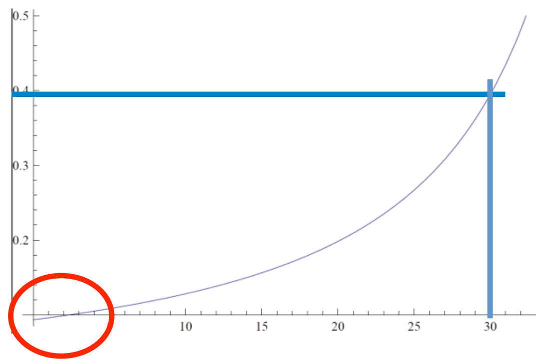
β function must be positive　B>0

CW mechanisms = dimensional transmutation

Coleman-Weinberg radiative breaking

λ

$\frac{\lambda\phi^4}{4}$



Symmetry is broken near the scale where the running coupling crosses zero.

$$M_{CW} = M_{UV}\exp(-\frac{\lambda_{UV}}{b} - \frac{1}{4})$$

Positive beta function in IR region

cf. Dimensional transmutation in QCD

$$\Lambda_{QCD} = M_{UV}\exp\left(-\frac{2\pi}{b_0\alpha_s(M_{UV})}\right)$$

But CW does not work in SM.

the **large top Yukawa** coupling **invalidates the CW** mechanism

Extension of SM is necessary !

Meissner Nicolai (07)

(B-L) extension of SM with flat Higgs potential at Planck

SM + B-L sector

- $U(1)_{B-L}$ gauge
- SM singlet scalar ϕ
- Right-handed ν

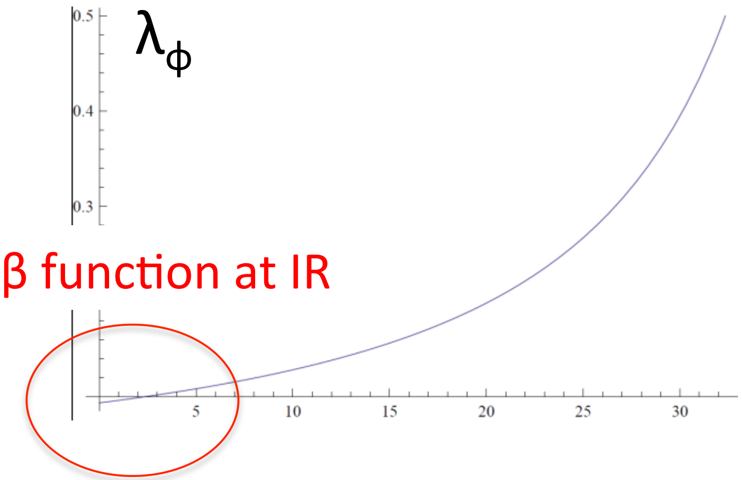
N Okada, Y Orikasa, & SI
0902.4050 (PLB)
0909.0128 (PRD)
1011.4769 (PRD)
1210.2848(PTEP)

"Occam's razor" scenario

that can explain

- 126 GeV Higgs
- Naturalness problem
- ν oscillation, baryon asymmetry

B-L symmetry is spontaneously broken via CW mechanism



$$\frac{d\lambda_\Phi}{dt} = \frac{1}{16\pi^2}\left(20\lambda_\Phi^2 + 2\lambda_{mix}^2 - \underline{\quad Tr\left[Y_N^4\right] + 96 g_{B-L}^4} + \lambda_\Phi\left(2Tr\left[Y_N^2\right] - 48 g_{B-L}^2\right)\right)$$

β function should be positive at IR

= Majorana Yukawa should not exceed the gauge coupling at IR

How does the EWSB occur ?

Our assumption (Flatness conditon for H) $V(H) = 0 \quad @M_{PL}$

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2}\Phi^2$$

classically conformal

126 GeV

key to relate EW and B-L @TeV

The coefficient must be small and negative.

$$\langle H \rangle = \sqrt{\frac{-\lambda_{H\Phi}}{\lambda_H}} M_{B-L}$$

Can the small scalar mixing be realized naturally?

→ Yes (Orikasa, SI 2012)

Scalar mixing can be generated via gauge mixing of $U(1)_Y$ and $U(1)_{B\text{-}L}$

★ U(1) mixing is radiatively generated

★ Then a small negative scalar mixing is radiatively generated

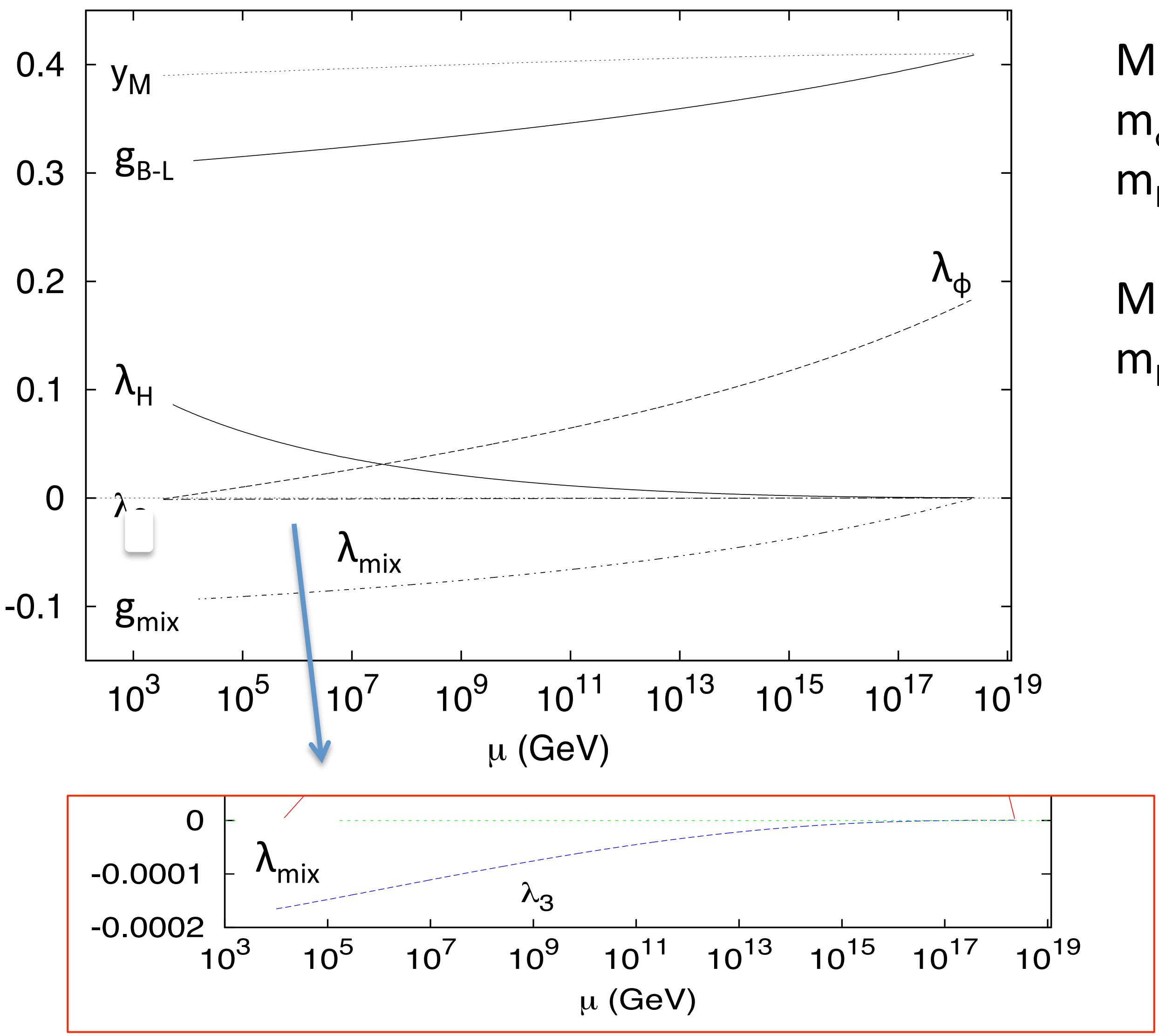
$$\frac{d\lambda_{H\Phi}}{dt} = \frac{1}{16\pi^2}\left(\boxed{6g_{B-L}^2 g_{mix}^2} + \lambda_{H\Phi} \times (\cdots)\right) \longrightarrow \lambda_{H\Phi} \sim -g_{B-L}^2 g_{mix}^2$$

The scalar mixing triggers EWSB.

The generated coefficient is generally very small and negative.
This triggers the EWSB and creates hierarchy between EW and B-L scales.

$$\langle H \rangle = \sqrt{\frac{-\lambda_{mix}}{\lambda_H}} M_{B-L} \sim c\frac{\alpha_{B-L}\alpha_Y}{\sqrt{\lambda_H}} M_{B-L}$$

A typical behavior of RGE



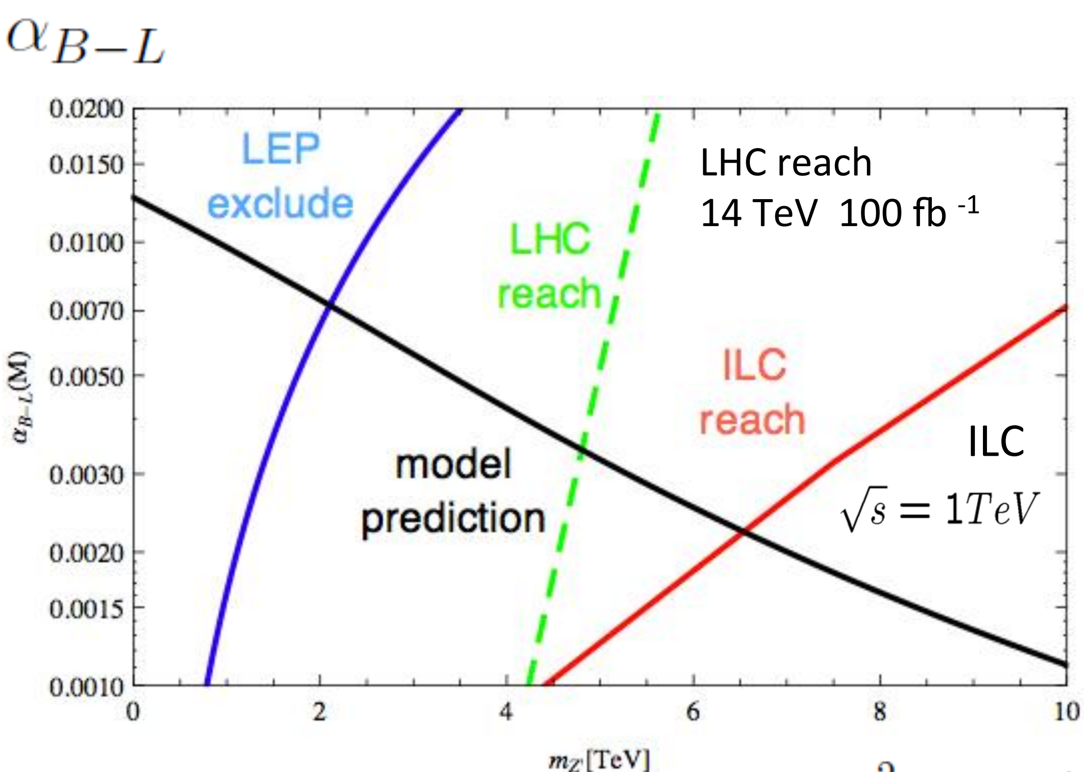
$M_{B\text{-}L}$ = 3.55 TeV,
m_ϕ = 200 GeV,
m_N= 2.8 TeV

M_{EWSB} = 246 GeV,
m_H = 126 GeV

A small negative scalar mixing is generated !!

Prediction of the model

In order to realize EWSB at 246 GeV,
B-L scale must be around TeV (for a typical value of $\alpha_{B\text{-}L}$).



$$M_{B-L} \sim \frac{1}{\alpha_{B-L}} \times 35 \text{ GeV}$$

$$m_{Z'} \sim \frac{1}{\sqrt{\alpha_{B-L}}} \times 250 \text{ GeV}$$

$$\boxed{m_\phi \sim 0.1 \ m_{Z'}}$$

$$m_{Z'}^2 = 16\pi\alpha_{B-L}(0)M_{B-L}^2$$

Y Orikasa, SI; 1210.2848(PTEP)

[4] Flatland model

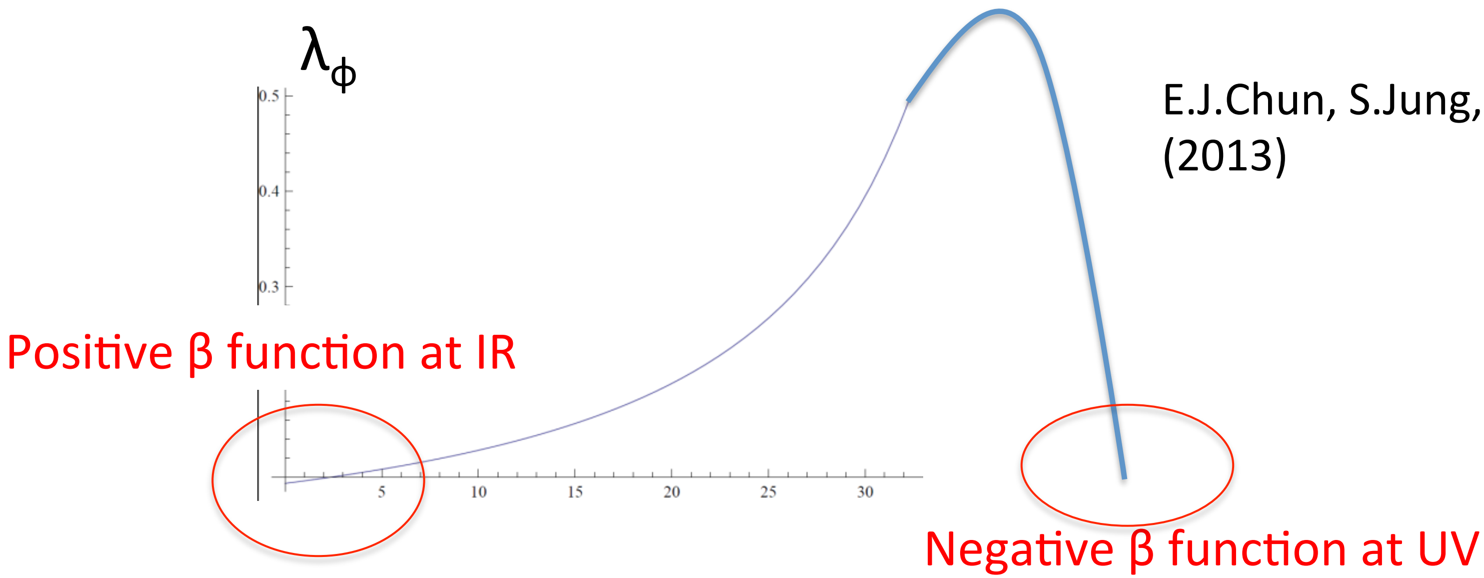
M. Hashimoto, Y.Orikasa, SI
to appear soon (2013)

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2 \Phi^2} + \cancel{m_\phi^2 \phi^2} + \boxed{\lambda_\phi \phi^4}$$

Can we further throw away the last term ?

Radiative generation of
scalar potential from nothing !!

If SSB occurs in Flatland, we need a behavior like



E.J.Chun, S.Jung, HM.Lee (2013)

$$\frac{d\lambda_\Phi}{dt} = \frac{1}{16\pi^2}\left(20\lambda_\Phi^2 + 2\lambda_{mix}^2 - \underline{\quad Tr\left[Y_N^4\right] + 96 g_{B-L}^4} + \lambda_\Phi\left(2Tr\left[Y_N^2\right] - 48 g_{B-L}^2\right)\right)$$

Balance between Y_N and g_{B-L} is necessary

A necessary and (almost) sufficient condition for both CW mechanism at IR and Flatland at UV to occur

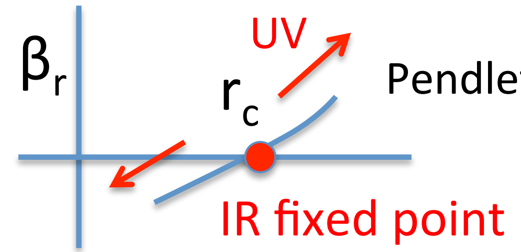
Gauge-Yukawa-Higgs system
(abelian gauge theory with a scalar ϕ and a fermion)

- g: gauge coupling
- y: Yukawa coupling
- λ: quartic self-coupling of scalar $\lambda\,\phi^4$

$$
\begin{aligned}
\beta_g &\equiv \mu\frac{\partial}{\partial\mu}g = \frac{a}{16\pi^2}g^3, \\
\beta_y &\equiv \mu\frac{\partial}{\partial\mu}y = \frac{y}{16\pi^2}\left[by^2 - cg^2\right], \\
\beta_\lambda &\equiv \mu\frac{\partial}{\partial\mu}\lambda = \frac{1}{16\pi^2}\left[-dy^4 + fg^4 + \cdots\right]
\end{aligned}
$$

a, b, c, d >0

$$16\pi^2\mu\frac{\partial}{\partial\mu}=\frac{\partial}{\partial t} \qquad r=y/g$$



Pendleton,Ross (81)

$$\begin{aligned}\dot g &= a g^3\\ \dot y &= y(by^2-cg^2)\\ \dot\lambda &= -dy^4+fg^4.\end{aligned} \longrightarrow \boxed{\dot r = bgy(r^2-r_c^2),} \qquad \boxed{r_c=\sqrt{\frac{a+c}{b}}.}$$

If CW occurs at IR (t=0) → $\beta_\lambda > 0$ → $r(t=0)<r_0.$ $\qquad \boxed{r_0=\left(\frac{f}{d}\right)^{1/4}.}$

increase

If Flatland at UR(t=t_{UV}) → $\beta_\lambda < 0$ → $r(t=t_{UV})>r_0$

$$r_c<r(t=0)<r_0<r(t_{UV})$$

$$K=\left(\frac{r_c}{r_0}\right)^2=\frac{a+c}{b}\sqrt{\frac{d}{f}}<1.$$

$$\boxed{K = \left(\frac{r_c}{r_0}\right)^2 = \frac{a+c}{b}\sqrt{\frac{d}{f}} < 1.}$$

In the B-L model with (N_g, N_ϕ, N)

- N_g : # of generations coupled with the B-L gauge
- N_ϕ : # of SM singlet scalars
- N : # of right-handed neutrinos with large Yukawa coupling

$$(3,1,1) = 1.22, \quad (3,1,2) = 1.3, \quad (3,1,3) = 1.27,$$
$$(2,1,1) = 0.982, \quad (2,1,2) = 1.04, \quad (1,1,1) = 0.74$$

No-go theorem for Flatland model with $N_g = 3$

If K is close to 1, the scalar mass m_ϕ becomes very light.

$$\lambda(M) = -\frac{1}{64\pi^2}\Big(- dy^4(M) + fg^4(M) \Big) + \mathcal{O}(\lambda^2)$$

$$m_\phi^2 \simeq -4\lambda M^2$$

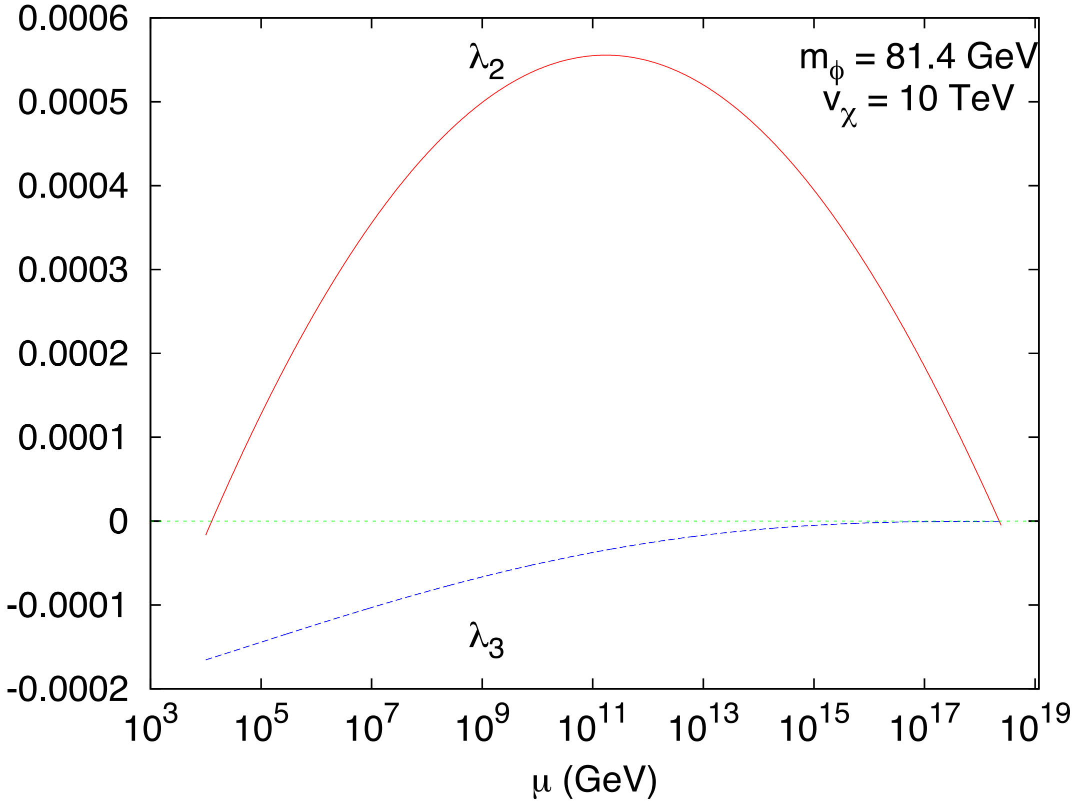
$$\longrightarrow \quad \frac{m_\phi^2}{M^2} \sim \frac{1}{16\pi^2}\Big(- dy^4(M) + fg^4(M) \Big) = \frac{dg^4(M)}{16\pi^2}\Big(- r^4(M) + r_c^4 \Big)$$

Mass of the scalar is proportional to the β function

$\boxed{K \sim 1 \rightarrow \quad r(M) \sim r_c \quad \rightarrow \quad m_\phi << M}$

$$(2,1,1) = 0.982,$$ N_g =2 model

Only the 2[nd] and 3[rd] generations have B-L charges.



M_{B-L} = 10 TeV,
m_ϕ = 81.4 GeV,
m_N= 7.7 TeV

M_{EWSB} = 246 GeV,
m_H = 126 GeV

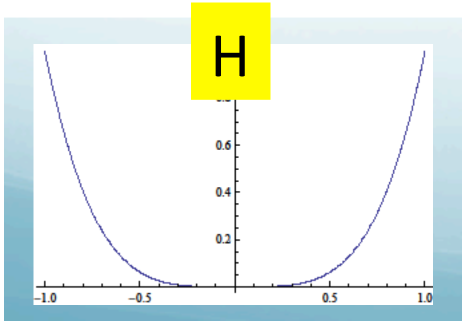
In this model, flavor mixing between 1[st] and 2,3nd generations is prohibited. → Froggatt Nielsen mechanism is necessary (Special flavor structure)

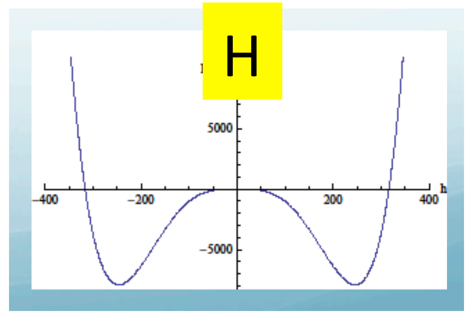
$$Y_D^{i3}\overline{\nu_R^i}H^\dagger l_L^3 \left(\frac{S}{\Lambda}\right)^k$$

[5] Summary

History of radiative EWSB

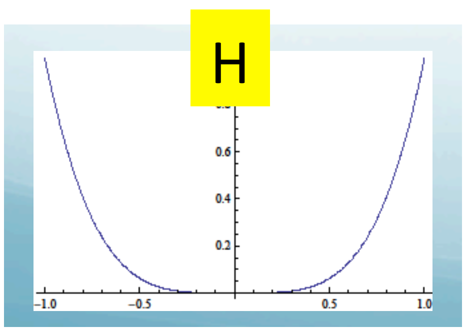
Naturalness





Coleman - Winberg (1973)

But CW does not work in SM. Introduce ϕ sector.



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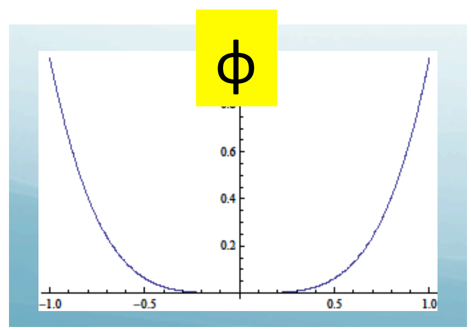

Meissner Nicolai (2007)
Foot et.al (2007)

Iso Okada Orikasa (2009/2)
Holthausen Lindner Schmidt (2009/11)

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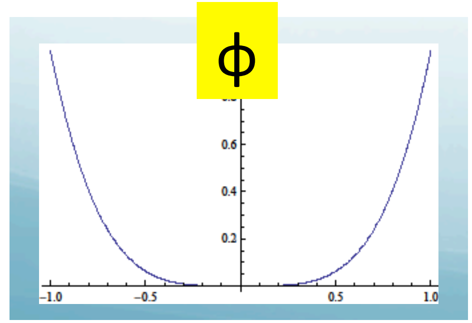
and many others
much later

126 GeV (stability)

flat potential

H

+



Iso Orikasa (2012)

Flatland model

flat potential

H

+

flat potential

ϕ

Chung Jung Lee (2013)
Hashimoto Iso Orikasa (2013)

Summary

- 126 GeV Higgs = border of the stability bound of SM vacuum.

  → Direct window to Planck scale → Flat Higgs potential @Planck

  Hint for the origin of Higgs in string theory
- Occam's razor scenario beyond SM

  "Classically conformal B-L model" is proposed

(1) it solves naturalness problem

(2) it explains why B-L breaking scale is around TeV.

(3) phenomenologically viable

Neutrino oscillation, resonant leptogenesis

(4) Prediction

Z' around several TeV, $M_\phi < M_{Z'}$, Leptogenesis at TeV

(5) Flatland scenario is possible only for N_g =1, 2

Future or on-going projects

Garny, Kartavsev, Hohenegger (11)
K. Shimada, M.Yamanaka, SI(2013) appear soon

- Resonant leptogenesis (low scale sea-saw)

  Kadanoff-Baym equation (quantum Boltzman)
- Origin of flat Higgs potential at Planck

  PNGB ? Moduli ? Gauge/Higgs ? Shift sym?

  Non-susy vaua of string with flat Higgs potential
- Non-susy GUT at the string scale

  Is supersymmetry really necessary?

  necessary for gravity sector (closed string)

  but may be not for open string sector?

  Brane susy breaking ? Antonidsis Dudas Sagnotti (99)
- Higgs inflation

Backup slides

RGE improved effective potential for large field (h >> v) $$V_{\rm eff}(h) = \frac{\lambda_{\rm eff}(h)}{4} h^4$$

RGE @1-loop $$\frac{d\lambda_H}{dt} = \frac{1}{16\pi}\left(24\lambda^2 \boxed{- 6Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g_1^4 + \cdots}\right)$$

Already known

It is related to Higgs mass as $M_h^2 = 2\lambda v^2$

Higgs mass controls the behavior of Higgs potential at large values of h.

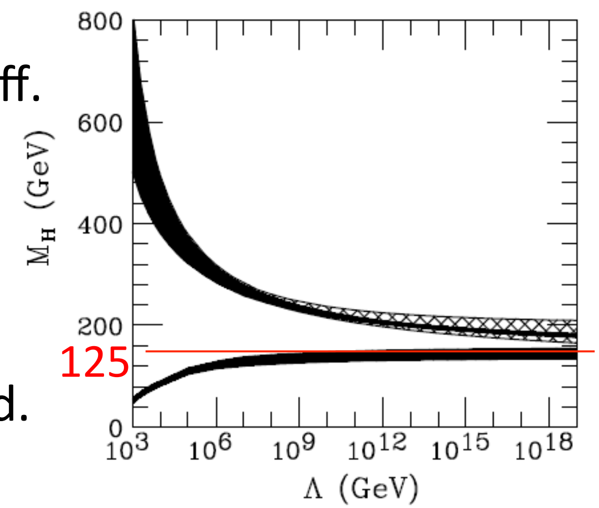
This gives two bounds for Higgs mass

(1) The quartic coupling does not blow up until UV cut-off.

M < 180 GeV (triviality bound)

(2) The quartic coupling does not become negative until UV cut-off. (Stability bound)

M = 125 GeV Higgs is very close to the stability bound.



「大統一のスケールはどこにあるべきか？」
ゲージ相互作用の統一には本当に超対称性が必要なのか？
プランク物理はプランクスケール直上か？

「超弦理論の真空に超対称性は必要？」
弦スケールから decouple した古典スケールのない有効理論とは？

「Sea-sawスケールは本当に 10^9 GeV ほど高くないとだめなのか？」
レプトン生成機構の見直し　　　　cf. Asaka Shaposhnikov
→ K.Shimada, M.Yamanaka, SI (to appear)

「宇宙項問題の再検討」
暗黒エネルギーは宇宙誕生時の量子効果と関係するか？
非平衡場の量子論をもっとまじめに考えるべきではないか。
→ H.Aoki, Y.Sekino, SI (to appear)